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REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CS-25

SPALL REPAIR OF WET CONCRETE SURFACES

by

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The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

This report describes the use of chemical materials that, if used improperly, may have adverse health and environmental effects. Reasonable caution should guide the preparation, repair, and cleanup phases of concrete repair activities involving potentially hazardous and toxic chemical substances. Manufacturer's directions and recommendations for the protection of occupational health and environmental quality should be carefully followed. Material Safety Data Sheets should be obtained from the manufacturers of such materials. In cases where the effects of a chemical substance on occupational health and environmental quality are unknown, chemical substances should be treated as potentially hazardous or toxic materials.

COVER PHOTOS:

TOP -- Eroded concrete with wet surface

BOTTOM -- Fabrication of slant-shear bond test specimen with wet concrete surfaces

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Because of the nature of the hydraulic structures over which the Corps of Engineers has responsibility, there are frequent requirements to repair spalled or eroded concrete that is underwater, close to the waterline, or in areas from which it is difficult to divert flow or dry the concrete. The purpose of this investigation was to evaluate the effectiveness of commercially available products in repair of concrete with wet surfaces.

Slant-shear bond and compressive strength tests were conducted on each of the 22 materials recommended for repair of spalls in wet concrete. Based on the results of these screening tests, eight materials were selected for additional laboratory tests including (a) bonding capacity in direct tension, (b) bonding capacity under flexural stress, (c) resistance to abrasion, (d) resistance to cycles of freezing and thawing, (e) impact resistance, and (f) thermal compatibility with concrete.

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19. ABSTRACT (Continued).

Test results and material costs were used in developing a rating system to compare the relative performance of the various materials. Overall performance ratings indicate two materials, an epoxy and a cement-based product, were nearly equal in outperforming the other products tested. Which of these two materials to be specified for a given repair will likely depend on the specific project requirements and critical material properties.

6a. & b. NAME OF PERFORMING ORGANIZATION (Continued).

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PREFACE

The study reported herein was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32303, "Application of New Technology to Maintenance and Minor Repair," for which Mr. James E. McDonald, US Army Engineer Waterways Experiment Station (WES), Structures Laboratory (SL), is Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program sponsored by HQUSACE. Dr. Tony C. Liu is the Technical Monitor for this work unit.

Mr. Jesse A Pfeiffer, Jr., is the REMR Coordinator in the Directorate of Research and Development, HQUSACE. The Overview Committee at HQUSACE for the REMR Research Program consists of Mr. James E. Crews and Dr. Liu. Mr. William F. McCleese, WES, is the REMR Program Manager.

The study was monitored by SL, WES, and conducted by the Singleton Materials Engineering Laboratory (SME), Tennessee Valley Authority, under Support Agreement WESSC-85-05/TV-67769A. All testing was conducted under the direct supervision of Mr. J. Floyd Best, Supervisor, Concrete and Soils Unit, under the general supervision of Mr. William H. Childres, Laboratory Supervisor, SME. The study was performed under the general supervision of Messrs. Bryant Mather, Chief, SL, and Kenneth L. Saucier, Chief, Concrete Technology Division (CTD), and under the direct supervision of Mr. McDonald, CTD. Messrs. Best and McDonald prepared this report. Final editing for publication of this report was provided by Ms. Gilda Miller, Editor, Information Products Division, Information Technology Laboratory, WES.

Commander and Director of WES is COL Larry B. Fulton, EN. Technical Director is Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
inches	25.4	millimetres
inch-pounds (force)	0.112985	newton metres
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.45359237	kilograms

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

SPALL REPAIR OF WET CONCRETE SURFACES

PART I: INTRODUCTION

Background

1. Because of the nature of the hydraulic structures over which the US Army Corps of Engineers (USACE) has responsibility, there are frequent requirements to repair spalled or eroded concrete that is underwater, close to the waterline, or in areas from which it is difficult to divert flow or dry the concrete. These repairs range from simple patching, that may be accomplished by project personnel, to extremely complex underwater work accomplished by contract.

2. In an effort to identify materials with potential for use in repair of spalled or eroded concrete under wet conditions, the US Army Engineer Waterways Experiment Station (USAEWES) conducted a literature search, contacted numerous manufacturers and suppliers, and placed an advertisement in the Commerce Business Daily. As a result, 13 different producers submitted a total of 22 products for testing.

Purpose

3. The purpose of this investigation was to evaluate the effectiveness of commercially available products in repair of concrete with wet surfaces.

Scope

4. Slant-shear bond and compressive strength tests were conducted on each of the 22 materials recommended for repair of spalls in wet concrete. Based on the results of these screening tests, eight materials were selected for additional laboratory tests including (a) bonding capacity in direct tension, (b) bonding capacity under flexural stress, (c) resistance to abrasion, (d) resistance to cycles of freezing and thawing, (e) impact resistance, and (f) thermal compatibility with concrete. Test results and material costs were used in developing a rating system to compare the relative performance of the various materials.

PART II: LABORATORY INVESTIGATION

5. Comparative performance testing was performed on 22 repair materials under closely controlled laboratory conditions. Special care was taken to follow manufacturer's instructions in mixing, placing, and curing for each product tested. Several of the patching materials were not recommended for thick continuous placements because of high heat generation and rapid setting characteristics. For these products, layers no thicker than 1 in. were placed in any one operation. In cases where specimen thickness exceeded 1 in., multiple layers were placed until the required thickness was obtained by allowing each layer to cool to ambient temperature prior to placing the succeeding layer.

6. Standardized testing procedures of the American Society for Testing and Materials (ASTM) or the USAEWES were used whenever possible. Where consensus standards did not exist, test procedures were developed by the performing organization and approved by the Corps of Engineers' Principal Investigator.

Screening Tests

7. While 18 of the 22 products submitted for testing were classified as patching materials, 4 products were advertised as bonding agents but were claimed to be useable as patching materials when mixed with a sand filler. All 4 of the bonding agents were epoxies, and 11 of the 18 patching materials were epoxies. The remaining seven patching materials were hydraulic cement-based products.

8. The screening process consisted of slant-shear bond strength tests (ASTM C 882, CRD-C 596 (ASTM 1987d)) on 3- by 6-in. cylinders and compressive strength tests (ASTM C 109, CRD-C 227 (ASTM 1987a)) on 2-in.-cube specimens. Slant-shear tests were conducted on specimens simulating both wet and dry concrete surfaces. To simulate wet surface conditions, the lower concrete dummy sections of the slant-shear specimens were stored in a moist room at 100 percent relative humidity until immediately prior to filling the upper half of the mold with repair material. The bond surface was examined just prior to filling the mold, and additional water was applied to the dummy section as necessary to obtain a glistening finish. Dry concrete surfaces were obtained by removing the dummy sections from the moist room and conditioning in

laboratory air for a minimum of 2 days prior to placing the repair material. Following fabrication, all test specimens were returned to the moist curing room until time of test, except that the epoxy materials were allowed the minimum amount of air curing recommended by the manufacturer prior to placing in the moist room.

9. Results of the bond and compressive strength tests are shown in Table 1. Although most of the products exhibited lower bond strength to wet surfaces than to dry surfaces, wet bond strengths for five patching materials and one bonding agent exceeded 2,000 psi. Of these six materials, only one (P-4) exhibited a higher bond to wet surfaces than to dry.

10. The wet bond strengths of the patching materials were generally proportional to their dry compressive strengths (Figure 1). Also, the wet bond strengths of the cement-based patching materials were generally higher than the epoxies for a given compressive strength.

Additional Laboratory Tests

11. Based on the results of the screening tests, four epoxy and four

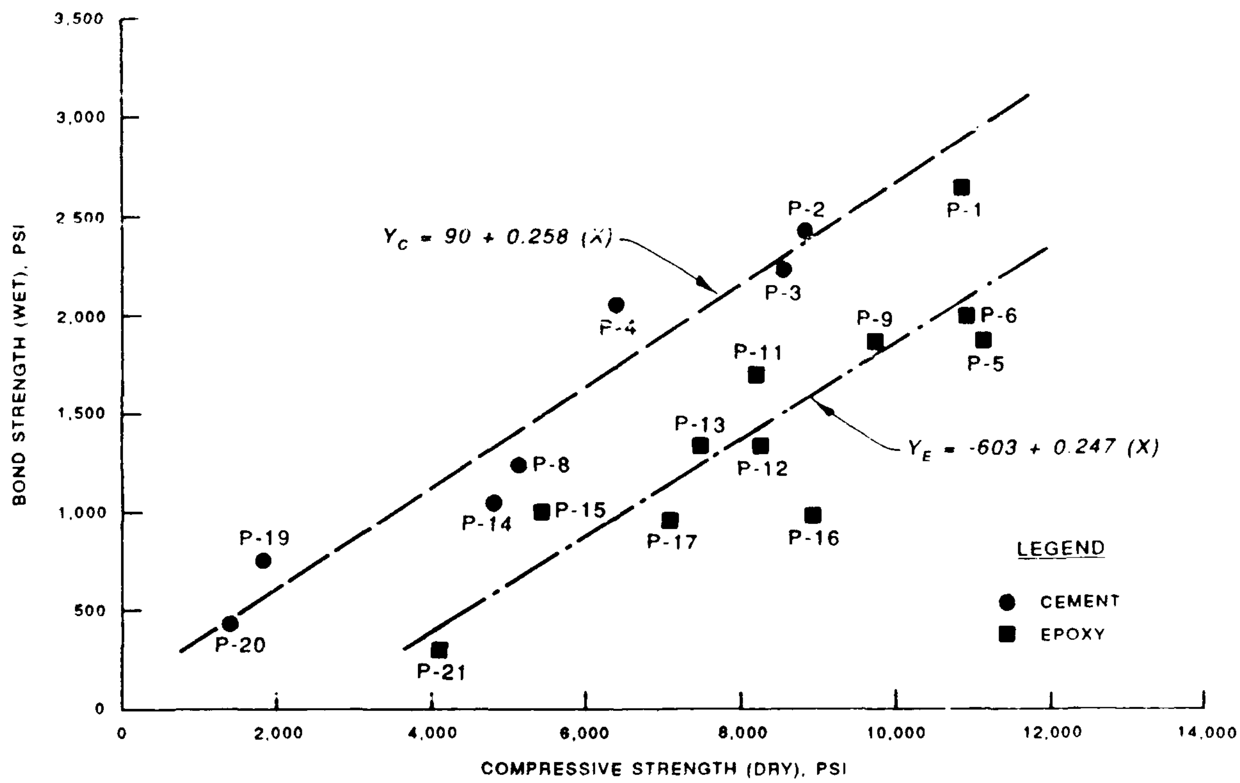

Figure 1. Results of screening tests on concrete patching materials

cement-based materials were selected for additional laboratory testing. Nine materials were originally selected for this testing, but product P-7 was eliminated after determining that its consistency was too thick for proper placement without specialized mixing equipment and placing procedures. The manufacturer described this product as a bonding agent rather than a patching material. A brief description of each material selected for additional laboratory testing follows.

Product Code	Description of Product
	Cement-Based Materials
P-2	Fast-setting and very rapid-hardening cement mortar. Initial set in about 15 min, final set about 30 min. Mix only with water for patches 1/2 to 2 in. deep. For deeper patches, clean 3/8-in. aggregate may be added as an extender.
P-3	Hydraulic cement-based, fiber-reinforced material. Manufacturer provides proprietary dry products and nonmetallic fibers; user supplies cement and sand. Initial set in approximately 15 to 30 min.
P-4	Cement-based, quick-setting hydraulic compound. Requires addition of water only. Very rapid set (3 to 5 min) will require multiple layering for deep patches.
P-8	Rapid-setting (3 to 5 min), cement-based hydraulic mortar. Add water only, do not retemper.
	Epoxy Materials
P-1	Three-component, modified epoxy resin-based grout. Recommended for grouting in submerged conditions. Working time about 30 to 40 min at 75° F, full cure time about 24 hr. Aggregate supplied in kit may be varied.
P-5	Three-component, fast-curing epoxy mortar. Working time about 30 min at 70° F, full cure varies with ambient temperatures. A 1-cu-ft unit includes 100 lb of sand.
P-6	Two-component, high-build epoxy coating. Recommended for repairs to wet or submerged concrete. Normal pot life about 4 hr, final cure about 4 days. Can add one to one and one-half parts sand (user-supplied), if desired.
P-9	Two-component, 100-percent solids epoxy grout. Pot life about 60 min at 77° F, and 7 days recommended for full cure. May add fillers up to seven parts by volume.

Bonding capacity in direct tension

12. To determine the adhesive bond developed between the patching

materials and a concrete substrate, direct tensile tests were performed similar to those previously reported by Causey (1984). Each patching material was used to fill a 10-in.-square, 1-in.-deep cavity in a horizontal 4-in.-thick concrete test slab. Surface preparation of the base concrete included scarification and water saturation by storing in a 100-percent humidity room prior to making the surface repair. After curing the patch in accordance with the manufacturer's recommendations, four equally spaced 3-in.-diam cores were drilled within the 10-in.-square patched area (Figure 2) to a depth approximately 1 in. below the patching material/concrete interface. Steel pullout plates were epoxied to the surface of the patching material and loaded in tension after the epoxy had hardened. Load was applied using a center-hole ram and load cell shown in Figure 3 until failure occurred either in the concrete substrate or at the bond interface between the concrete and the patching material.

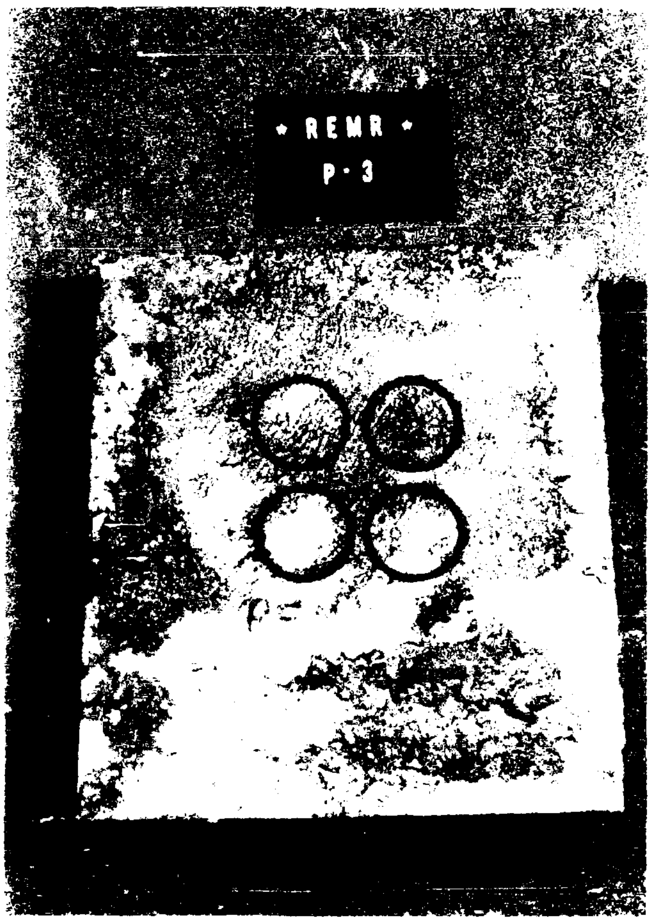

Figure 2. Direct tension bond test specimen after coring

Figure 3. Loading apparatus for direct tension bond test

Bonding capacity
under flexural stresses

13. In some applications, the surface patch may be subject to lateral tension and shear stresses rather than normal tensile forces. To simulate these conditions, horizontal test slabs identical to those used in the direct tensile tests were fabricated with a 10- by 10- by 1-in. cavity (Figure 4). After scarifying and filling the premoistened cavity with the patching material (Figure 5), 3- by 4- by 15-in. beam specimens were sawed for flexural strength tests (Figure 6). All epoxy patching materials were cured a minimum of 14 days prior to sawing beam specimens, and cement-based products were cured a minimum of 28 days. Each of the sawed beam specimens was tested for flexural strength using the center-point loading prescribed by ASTM Method C 293, CRD-C 17 (ASTM 1987b), with the 1-in. layer of repair material oriented

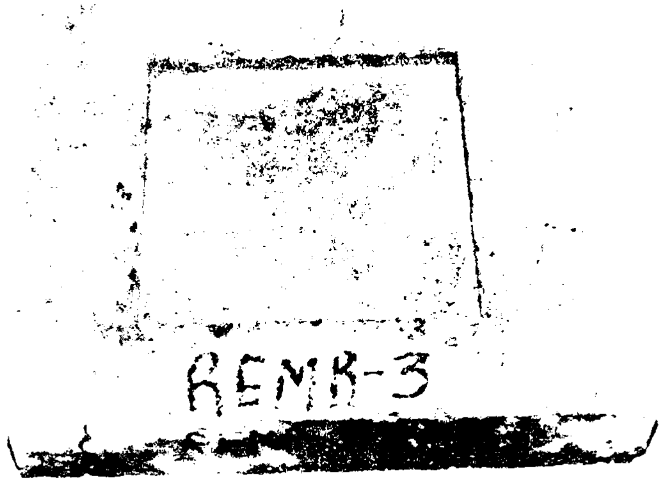

Figure 4. Concrete test slab with 10- by 10- by 1-in. cavity prior to scarification

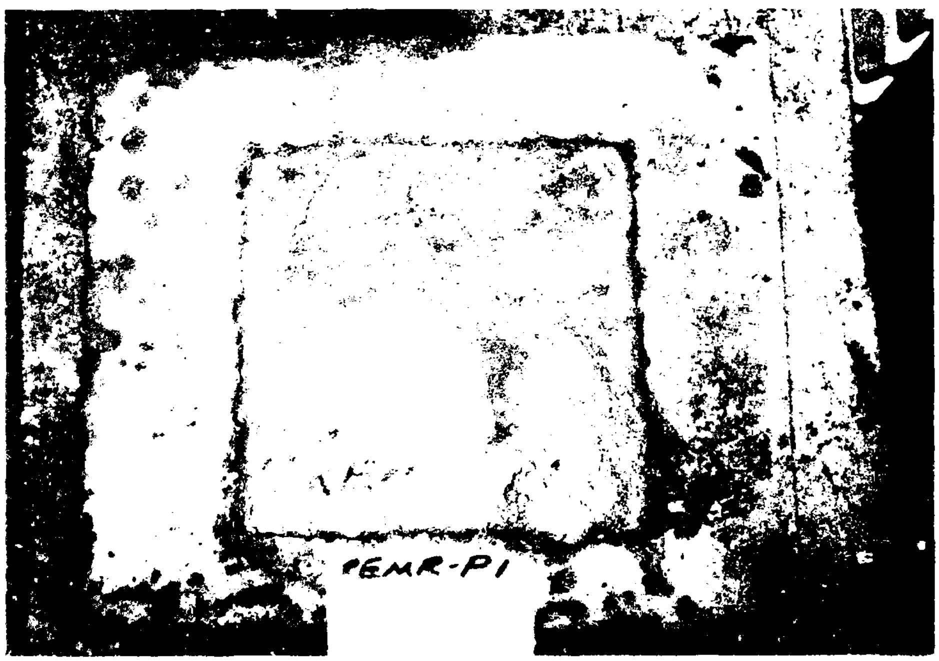

Figure 5. Concrete test slab after filling cavity with patching material

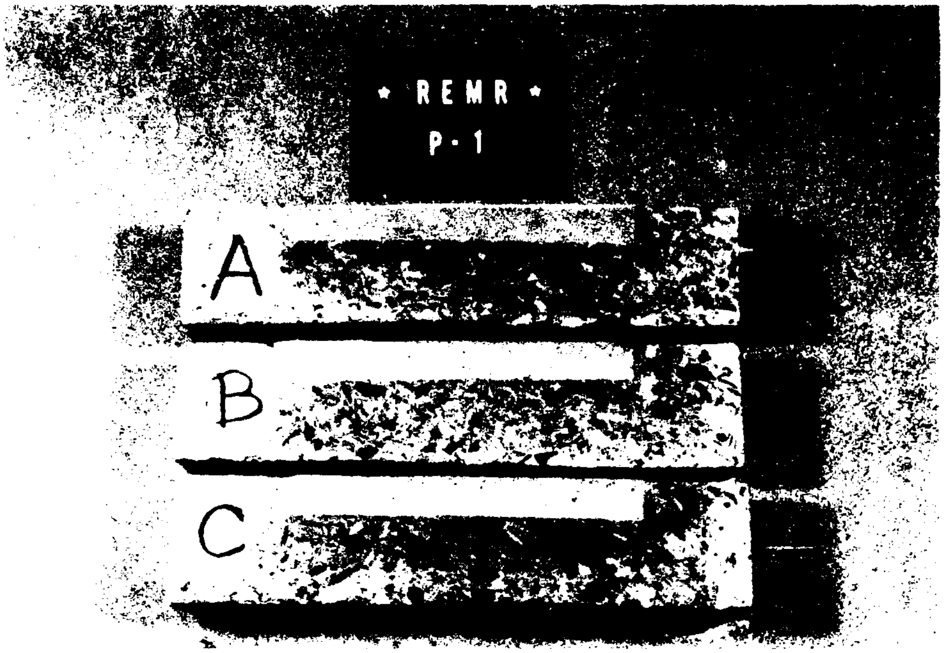

Figure 6. Typical flexural test beams showing patched cavity

along the lower tensile beam surface (Figure 7). Three beams for each material were tested.

Figure 7. Typical center-point flexural test with patching material along lower face

Resistance to abrasion

14. The ability of the patching materials to resist abrasive wear was compared by performing the underwater abrasion test described in CRD-C 63 (USAEWES 1980). Three 12-in.-diam by 4-in.-thick specimens were cast from each material. After curing for 7 days, each specimen was placed in a separate abrasion apparatus shown in Figure 8 and exposed to six consecutive 12-hr cycles of underwater abrasion. Specimens were removed and weighed between each cycle to determine weight loss with respect to the number of exposure cycles.

Resistance to freezing and thawing

15. Three beam specimens, 3 by 4 by 16 in., were fabricated from each product using gang molds shown in Figure 9. All specimens were cured a minimum of 28 days. Using two freeze-thaw cabinets, three specimens each of the epoxy products were placed in one cabinet and three specimens each of the cement-based products were placed in the other. All specimens were then exposed to 300 cycles of alternating freezing and thawing in water in accordance with Procedure A of ASTM C 666, CRD-C 20 (ASTM 1987c). Specimens were removed approximately every 30 cycles and weighed to compare weight loss with the number of exposure cycles.

Impact resistance

16. Three specimens, 12 by 12 by 2 in., were fabricated from each material. After curing a minimum of 7 days, each specimen was supported on a bed of loose sand and an 85-lb weight having a 2-1/2-in.-diam hemispherical contact surface was dropped onto the center of the specimen from progressively increasing heights until the specimen cracked. The minimum drop height to produce cracking was recorded and the required energy in inch-pounds was calculated. Figure 10 shows the drop-weight apparatus used for these tests.

Thermal compatibility
with concrete

17. Three specimens, 3 by 3 by 11-1/4 in., were made with each of the patching materials. Stainless steel studs were embedded in each end with a nominal distance of 10 in. between them. Specimens were molded and allowed to cure 14 days prior to testing. After curing, specimens were placed in laboratory air for 24 hr to allow for surface drying of specimens, and initial length measurements were made at an ambient temperature of 73° F. Specimens were then placed in an environmental room at 40° F until they reached

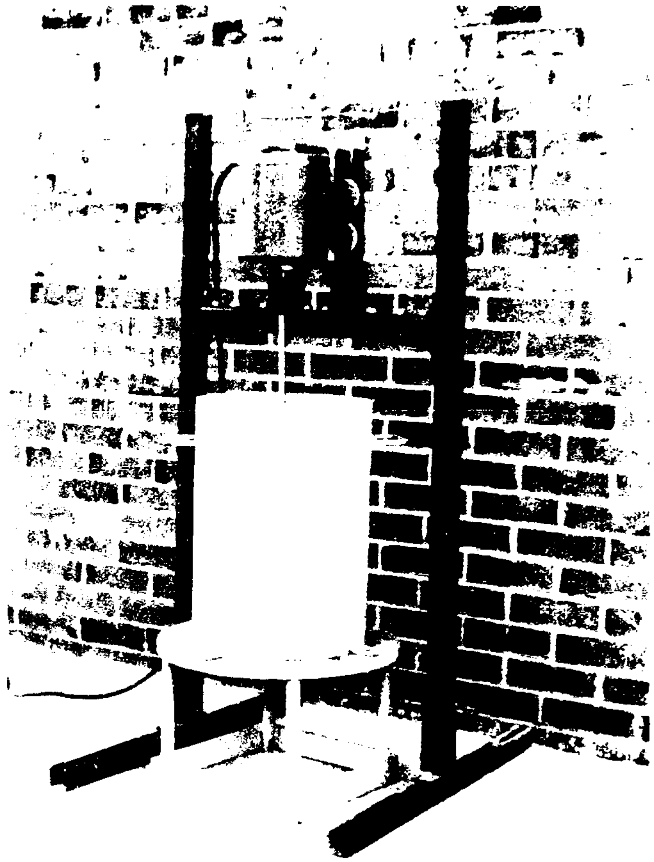

Figure 8. Underwater abrasion test apparatus

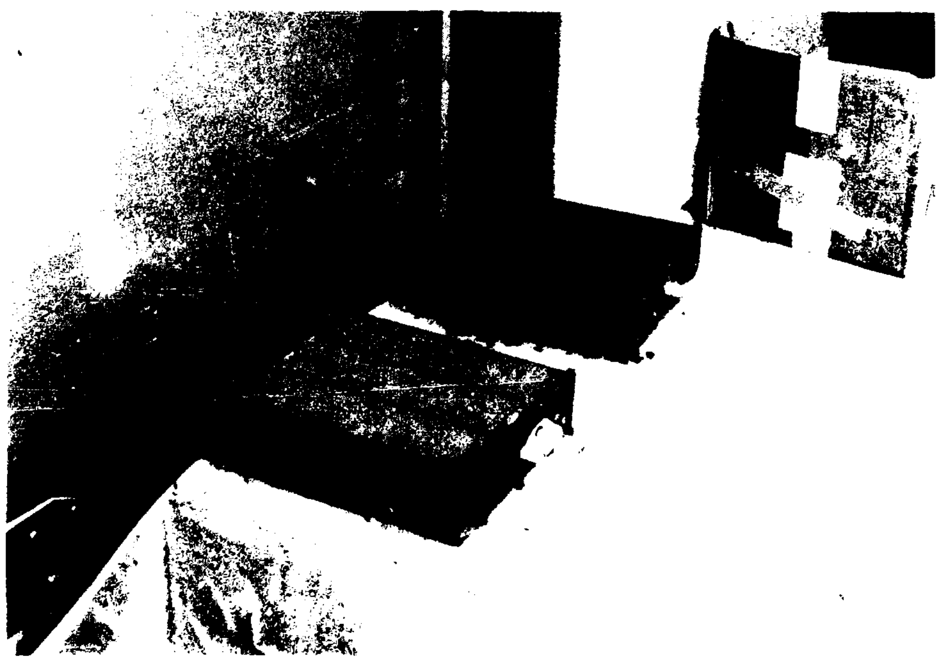

Figure 9. Gang molds used to fabricate freeze-thaw specimens

Figure 10. Drop-weight apparatus for impact tests

equilibrium and measurements of length were again made. Specimens were then subjected to an environmental room temperature of 140° F and the length measured after equilibrium was reached.

PART III: TEST RESULTS

Slant-Shear Bond and Compressive Strength

18. Results of slant-shear bond and compressive strength tests performed during the product screening phase are presented in Table 1. Excluding product P-7, products P-1 through P-9 were selected for additional laboratory testing. Product P-1, an epoxy material, had the highest bond strength for wet surfaces, and was second only to product P-9 in bonding to dry surfaces. Of the cement-based products, product P-2 was highest in wet surface bond strength, and was second among all products in this category. As expected, all four epoxy products had higher compressive strengths than any of the cement-based materials, averaging 10,600 psi compared to 7,250 psi for the cement mortars. Wet bond strengths for the two types of materials were more nearly equal averaging 1,990 and 2,110 psi for the cement-based and epoxy materials, respectively. A graphical comparison of slant-shear bond test results is shown in Figure 11.

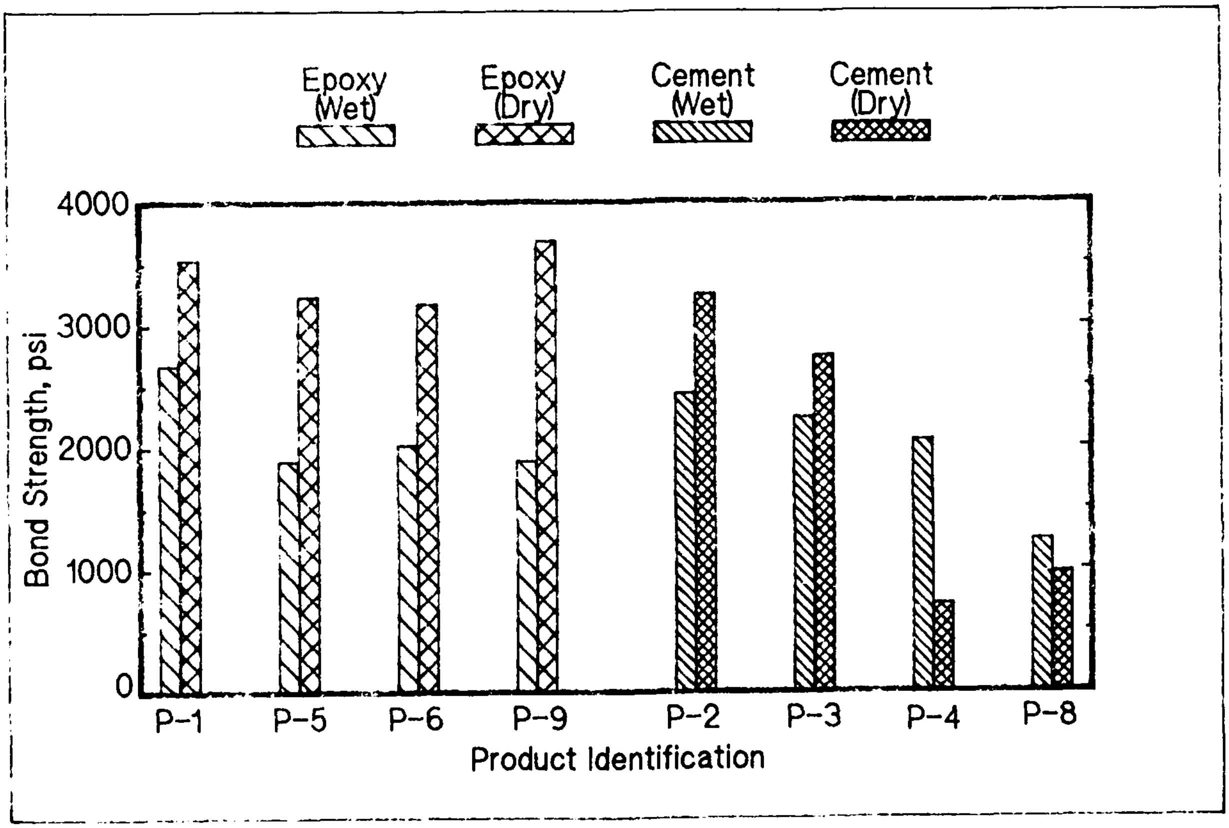

Figure 11. Comparison of slant-shear bond strengths

Bonding Capacity in Direct Tension

19. Epoxy material P-5 was the superior performer in the direct tension bond tests, averaging 320 psi breaking stress with failure occurring in the concrete in all cases. No other epoxy did nearly as well, ranking below even the lowest strength cement product. Of the cement-based materials, product P-2 was best, causing concrete failure in all cases at an average stress of 195 psi. Product P-3 was also a good performer at 175 psi. Results of all direct tensile bond tests are shown in Table 2. Figure 12 is a bar chart showing the relative performance of all products tested.

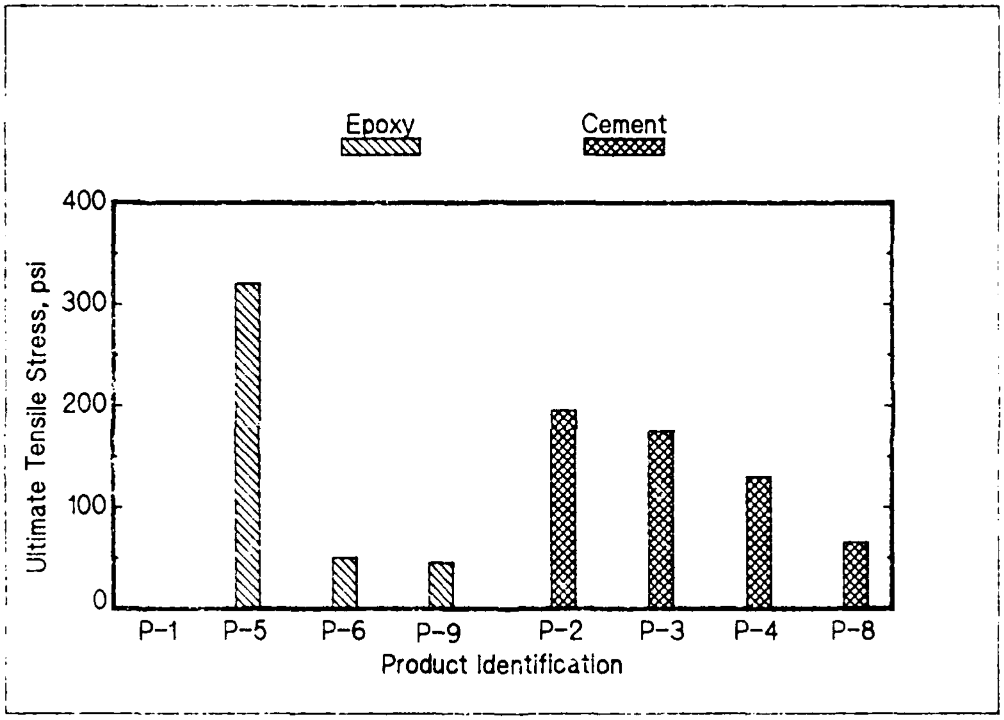

Figure 12. Bonding capacity in direct tension

Bonding Capacity Under Flexural Stress

20. Because of their higher tensile strengths, the epoxy materials generally performed better than cementitious products in the center-point beam test. Epoxy product P-5 was again the best performer, but three of the four epoxies had higher moduli of rupture than any of the cement-based products. Of the cement-based materials, products P-3 and P-2 were good performers with a modulus of rupture of 1,390 and 1,320 psi, respectively. Typically, beam

failure initiated at midspan with the crack going through the patching material for the cement-based products, while in most instances the epoxy materials had sufficient strength to force the point of crack initiation along the tensile beam face to the interface between the concrete and the patching material. The modulus of rupture for each specimen is listed in Table 3 while a comparative bar chart is shown in Figure 13.

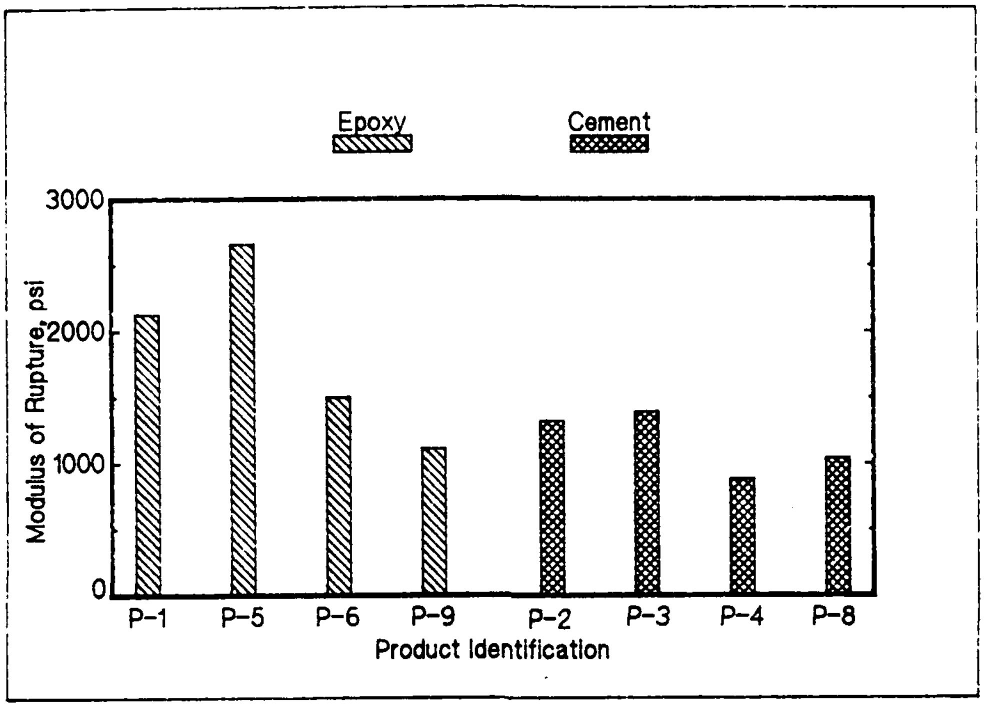

Figure 13. Bonding capacity under flexural stress

Resistance to Abrasion

21. Weight losses in the underwater abrasion test were significantly higher for the cement-based materials than the epoxy products (Table 4). The only epoxy product showing any measurable weight loss after 72 hr was product P-9, with 3 percent loss. The cement-based materials collectively averaged about 14 percent loss after 72 hr, with product P-3 having the lowest at 11 percent and product P-8 having the highest at 20 percent. Overall, abrasion-erosion losses were inversely proportional to the compressive strength of the repair material (Figure 14).

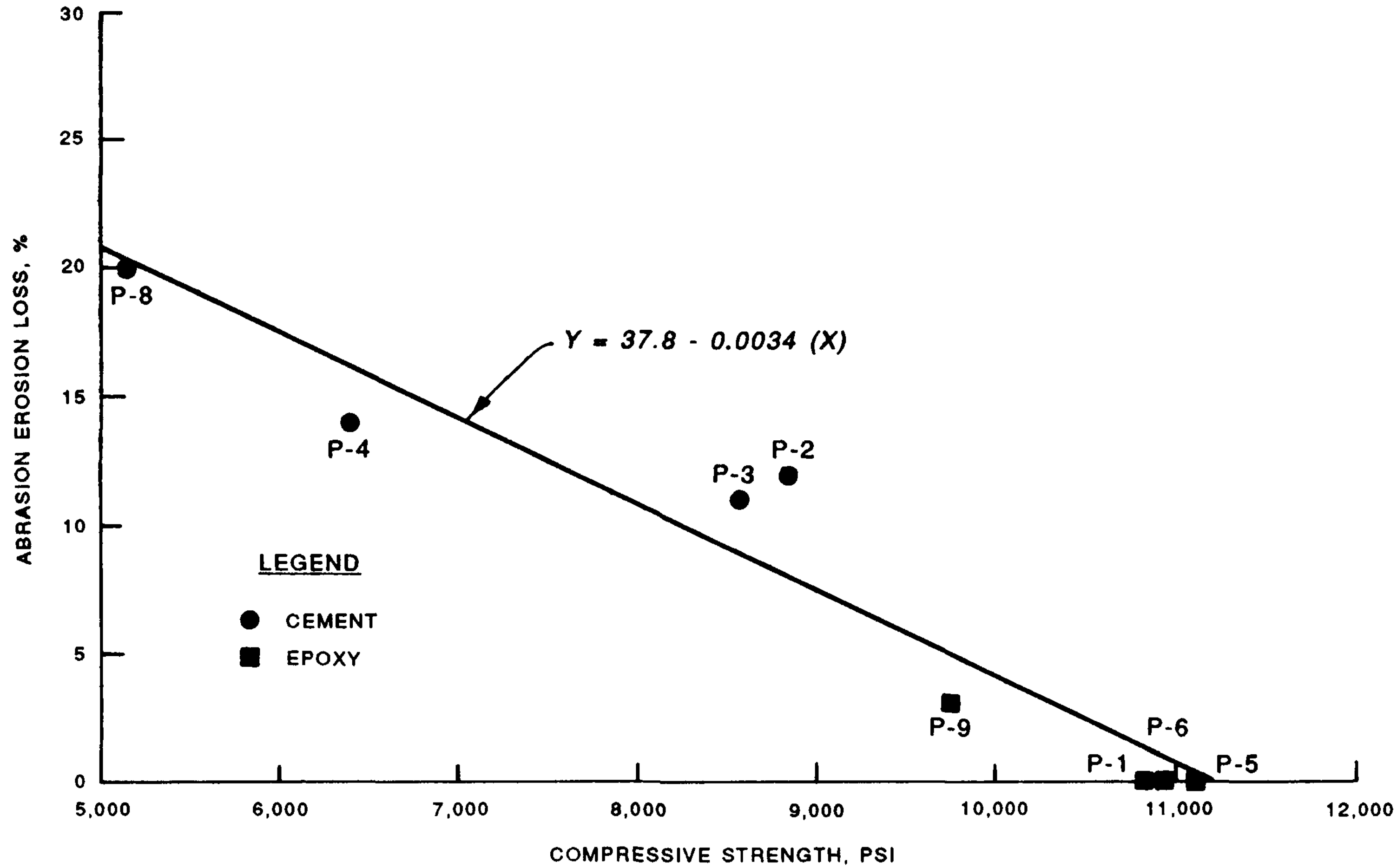

Figure 14. Correlation between abrasion-erosion loss and compressive strength

Resistance to Freezing and Thawing

22. Resistance to freezing and thawing of all products tested was excellent with one exception. Product P-8 started to exhibit substantial weight loss after about 80 cycles, and eventually all specimens broke in half after an approximate 50-percent weight loss. None of the other seven products showed any measurable weight loss after more than 300 cycles. One of the specimens from product P-4 split longitudinally after 180 cycles, but failure appeared to occur along a cold joint formed between layers when fabricating the specimen. Test specimens for this product were cast in three layers due to its rapid setting characteristics. Table 5 shows individual specimen weight losses at intervals of about 30 cycles.

Impact Resistance

23. Epoxy products P-1, P-5, and P-6 were clearly superior to the remaining patching materials in impact resistance, having more than three times the energy-absorbing capability of the others. Epoxy P-9 was only slightly better than the cement-based materials, between which no discernible difference was noted. If used for future comparisons of patching materials, the drop-weight method used in this study should be revised to provide less mass in the falling weight. This would allow the operator to better differentiate between products having similar impact resistance. Results for the impact tests in this study are summarized in Table 6 and illustrated in Figure 15.

Thermal Compatibility with Concrete

24. All of the epoxies had coefficients of thermal expansion higher than that of concrete, ranging from 13.6 to 27.2 millionths/°F. Of the cement-based products, P-8 had only about one-half of the thermal expansion coefficient of typical concrete, while the remaining three products were within the expected concrete range of 4 to 7 millionths/°F. In most instances, however, concrete is compatible with materials having coefficients of thermal expansion three or four times higher or lower than concrete. Differences of this magnitude will produce strains less than one thousandth for all but extreme temperature variations. For this reason, it is felt that

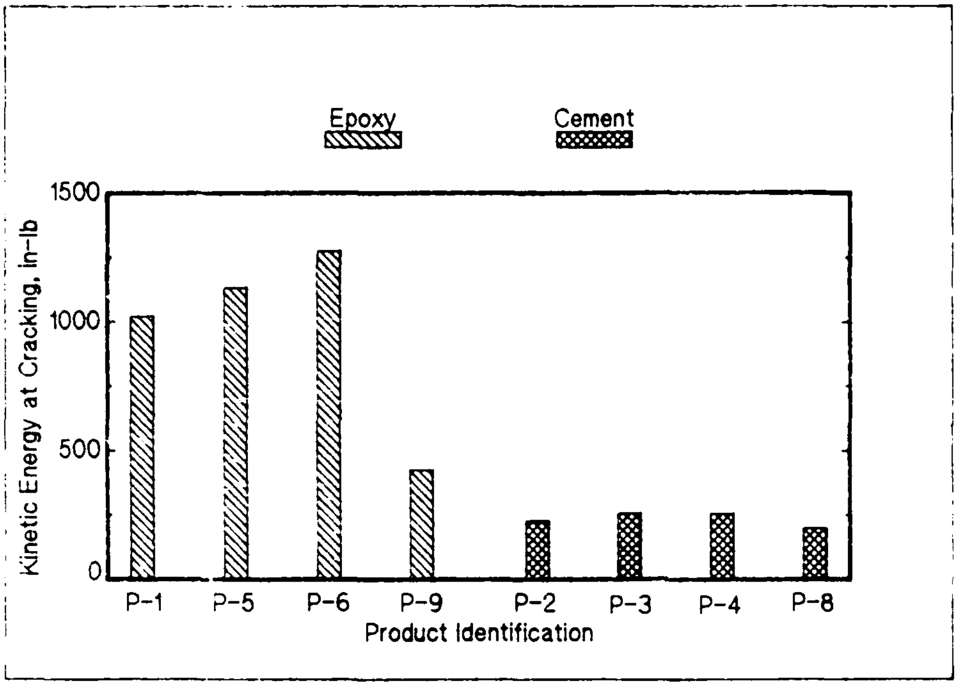

Figure 15. Impact test results

products P-5 and P-9 should be thermally compatible with concrete for most applications, while products P-1 and P-6 may be marginal in some instances. Results of thermal expansion tests are shown in Table 7 and Figure 16.

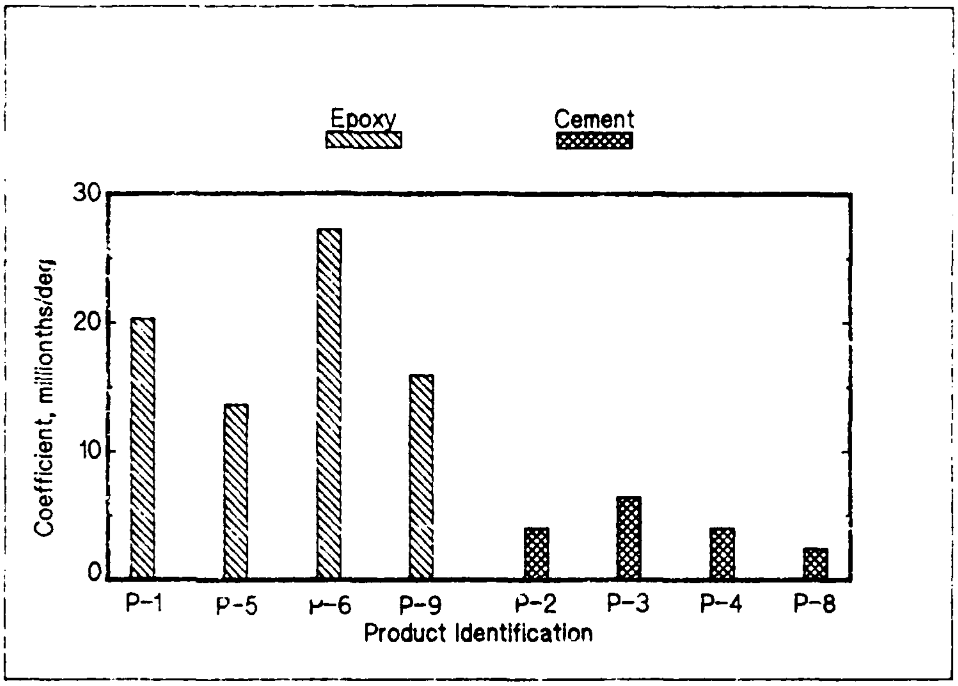

Figure 16. Coefficients of thermal expansion

PART IV: CONCLUSIONS

25. A comparative ratings system was developed based on the number of parameters evaluated in this investigation. While such a system is somewhat arbitrary, it can serve as a useful selection guide when considering a number of products for use under specified construction applications. Tables 8 and 9 were assembled to provide information from which product cost and performance data could be compared to arrive at a weighted performance rating for all materials tested. Costs per unit volume shown in Table 8 were calculated based on package prices and yield data provided by the product manufacturers when the program was initiated in 1987. Table 9 includes rankings of each material for each of the tests conducted in this investigation in addition to overall performance ratings and ratings by generic groups of epoxies and cements. Numerical ratings were calculated by assigning eight points for rank No. 1, seven points for rank No. 2, etc., for the overall comparison, and four points for rank No. 1, three points for rank No. 2, etc., for the generic group rankings.

26. In conclusion, overall performance ratings indicate products P-5 and P-3 to be nearly equal in outperforming the other products tested (Figure 17). These two materials were followed closely in the performance ratings

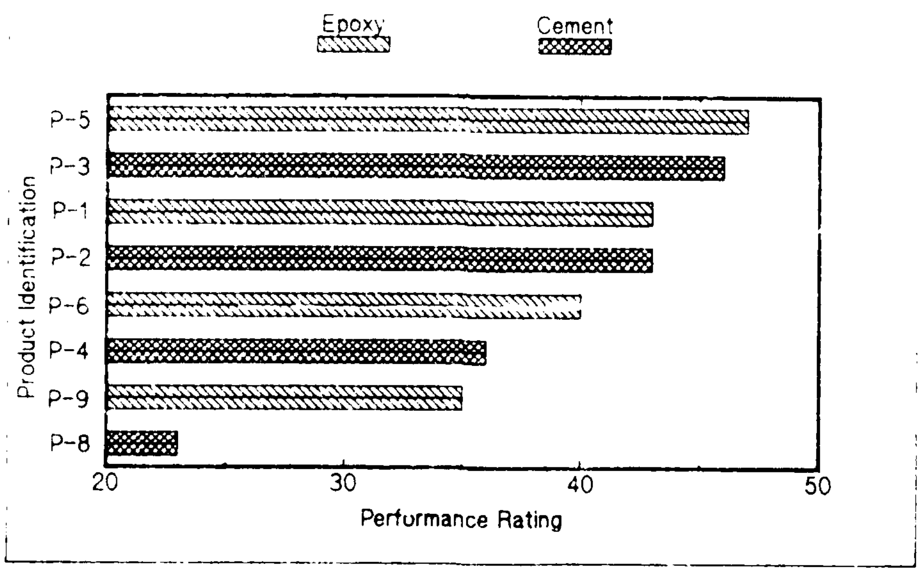

Figure 17. Overall performance ratings for individual repair materials

by products P-1 and P-2. With two each of the top performing products being epoxy materials (P-5 and P-1) and cement-based products (P-3 and P-2), the choice of which type of material should be specified will likely depend on the specific job requirements and critical material properties. If thermal compatibility, bond to wet concrete, and/or cost are of highest priority, product P-3 is likely the material of choice. However, if resistance to abrasion and impact are primary considerations, product P-5 may be the appropriate repair material. For highly specialized uses, some of the remaining six products tested may be best suited to provide the desired performance. In all instances, products selected from Table 9 for use in abnormal or harsh environments should be verified prior to use by laboratory qualification tests.

REFERENCES

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Table 1

Results of Screening Tests

Product Code		Bond Strength, psi (ASTM C 882 (ASTM 1987d)) Wet Surface	Dry Surface	Compressive Strength, psi (ASTM C 109 (ASTM 1987a))
		Patching Compounds		
P-1		2,619 (B)	3,539 (A)	10,750
		2,477 (B)	3,609 (A)	10,575
		2,902 (B)	3,432 (A)	11,250
	Avg	2,670	3,530	10,860
P-2		2,972 (B)	3,185 (B)	8,825
		1,840 (B)	3,255 (B)	8,688
		2,477 (B)	3,291 (B)	9,025
	Avg	2,430	3,240	8,850
P-3		2,123 (B)	2,902 (B)	8,250
		2,335 (B)	3,008 (B)	8,750
		2,265 (B)	2,300 (B)	8,750
	Avg	2,240	2,740	8,580
P-4		2,052 (B)	708 (B)	6,600
		2,052 (B)	708 (B)	6,125
		--	--	6,500
	Avg	2,050	710	6,410
P-5		1,805 (B)	3,185 (A)	10,750
		1,663 (B)	3,326 (A)	11,125
		2,194 (B)	3,185 (A)	11,500
	Avg	1,890	3,230	11,120
P-6		2,052 (B)	3,255 (A)	11,000
		2,123 (B)	3,079 (A)	11,000
		1,875 (B)	--	10,750
	Avg	2,020	3,170	10,920
P-8		1,040 (B)	1,224 (B)	5,250
		955 (B)	722 (B)	5,125
		1,716 (B)	248 (B)*	5,088
	Avg	1,240	970	5,150

(Continued)

Note: (A) indicates failure occurred in concrete.
(B) indicates failure occurred at bonded surface.
-- indicates no specimen.
N/A indicates that compression strengths of bonding agents were not determined.
* Not included in the average.

Table 1 (Continued)

Product Code		Bond Strength, psi (ASTM C 882 (ASTM 1987d))		Compressive Strength, psi (ASTM C 109 (ASTM 1987a))
		Wet Surface	Dry Surface	
		Patching Compounds (Continued)		
P-9		1,706 (B)	3,963 (A)	9,550
		2,017 (B)	3,397 (A)	9,975
		1,939 (B)	--	9,750
	Avg	1,890	3,680	9,760
P-11		1,769 (B)	3,255 (B)	8,125
		1,592 (B)	3,397 (B)	8,250
		1,769 (B)	3,432 (B)	8,325
	Avg	1,710	3,360	8,230
P-12		1,345 (B)	2,406 (B)	8,250
		1,238 (B)	2,265 (B)	8,325
		1,486 (B)	2,548 (B)	8,250
	Avg	1,360	2,410	8,280
P-13		1,274 (B)	1,875 (B)	7,400
		1,486 (B)	2,123 (B)	7,575
		1,309 (B)	2,265 (B)	7,525
	Avg	1,360	2,090	7,500
P-14		998 (B)	248 (B)	4,875
		1,104 (B)	177 (B)*	4,850
		--	354 (B)	4,788
	Avg	1,050	260	4,840
P-15		991 (B)	1,699 (B)	5,350
		991 (B)	1,550 (B)	5,475
		1,083 (B)	1,500 (B)	5,500
	Avg	1,020	1,580	5,440
P-16		998 (B)	3,192 (A)	8,950
		984 (B)	2,725 (A)	8,925
		1,005 (B)	--	8,975
	Avg	1,000	2,960	8,950
P-17		991 (B)	1,769 (B)	7,050
		991 (B)	1,982 (B)	7,088
		920 (B)	2,123 (B)	7,250
	Avg	970	1,960	7,130
P-19		708 (B)	778 (B)	1,875
		778 (B)	708 (B)	1,875
		--	--	1,788
	Avg	740	740	1,850

(Continued)

* Bad specimen unable to compact due to fast set but included in the average.

Table 1 (Concluded)

Product Code		Bond Strength, psi (ASTM C 882 (ASTM 1987d)) Wet Surface	Bond Strength, psi (ASTM C 882 (ASTM 1987d)) Dry Surface	Compressive Strength, psi (ASTM C 109 (ASTM 1987a))
		Patching Compounds (Continued)		
P-20		418 (B)	318 (B)	1,400
		538 (B)	340 (B)	1,400
		--	--	1,400
	Avg	430	330	1,400
P-21		283 (B)	1,486 (A)	4,063
		212 (B)	1,557 (A)	4,075
		460 (B)	1,557 (A)	4,200
	Avg	320	1,530	4,110
		Bonding Agents		
P-7		1,982 (B)	1,875 (B)	N/A
		2,052 (B)	1,734 (B)	N/A
		2,052 (B)	2,229 (B)	N/A
	Avg	2,030	1,950	
P-10		1,663 (B)	1,486 (B)	N/A
		1,663 (B)	1,415 (B)	N/A
		1,840 (B)	1,628 (B)	N/A
	Avg	1,720	1,510	
P-18		778 (B)	672 (B)	N/A
		849 (B)	651 (B)	N/A
		796 (B)	598 (B)	N/A
	Avg	810	640	
P-22		177 (B)	432 (B)	N/A
		212 (B)	389 (B)	N/A
		226 (B)	481 (B)	N/A
	Avg	200	430	

Table 2

Bond Capacity in Direct Tension

Product Code	Tensile Stress, psi	Remarks
P-1	--	Bond broke between concrete and patch material during coring process
	--	Bond broke between concrete and patch material during coring process
	--	Bond broke between concrete and patch material during coring process
P-2	227	Bond between concrete and patch material failed
	202	Bond between concrete and patch material failed
	188	Bond between concrete and patch material failed
	162	Bond between concrete and patch material failed
	Avg 195	
P-3	87	Concrete broke near bond with patch material
	220	Concrete broke near bond with patch material
	200	Concrete broke near bond with patch material
	198	Concrete broke near bond with patch material
	Avg 175	
P-4	--	Bond broke between concrete and patch material during coring process
	--	Bond broke between concrete and patch material during coring process
	70	Concrete broke
	186	Patch material broke
	Avg 130	
P-5	378	Concrete broke near the bond with patch material
	155	Concrete broke at the bond with patch material
	287	Concrete broke
	453	Concrete broke near the bond with patch material
	Avg 320	
P-6	--	Bond broke between concrete and patch material during coring process
	39	Failed at bond between concrete and patch material
	--	Bond failed between concrete and patch material during coring process
	63	Failed at bond between concrete and patch material
	Avg 50	
P-8	108	Concrete broke
	53	Concrete broke
	--	Bond failed between concrete and patch material during coring process
	31	Bond failure between concrete and patch material
	Avg 65	
P-9	--	Bond broke between concrete and patch material during coring process
	55	Bond failure between concrete and patch material
	--	Bond broke between concrete and patch material during coring process
	36	Bond failure between concrete and patch material
	Avg 45	

Table 3

Bonding Capacity Under Flexural Stress

ASTM C 293 (ASTM 1987b)

Product Code		Flexural Strength, psi	Remarks
P-1		2,033	Broke outside of patch material
		2,269	Broke outside of patch material
		2,093	Broke outside of patch material
	Avg	2,130	
P-2		1,273	Broke through patch material
		1,255	Broke through patch material
		1,445	Broke through patch material
	Avg	1,320	
P-3		1,378	Broke through patch material
		1,456	Broke through patch material
		1,325	Broke through patch material
	Avg	1,390	
P-4		993	Broke outside of patch material
		858	Broke through patch material
		775	Broke through patch material
	Avg	880	
P-5		2,843	Broke outside of patch material
		2,676	Broke outside of patch material
		2,454	Broke outside of patch material
	Avg	2,660	
P-6		1,379	Broke outside of patch material
		1,432	Broke outside of patch material
		1,702	Broke outside of patch material
	Avg	1,500	
P-8		1,034	Broke through patch material
		1,041	Broke through patch material
		1,050	Broke through patch material
	Avg	1,040	
P-9		928	Broke outside of patch material
		1,217	Broke inside of patch material
		1,196	Broke outside of patch material
	Avg	1,110	

Table 4

Underwater Abrasion Test - CRD-C 63 (USAEWES 1980)

Product Code		Percent Weight Loss					
		12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
P-1		0	0	0	0	0	0
		-1	-1	0	0	0	0
		-1	-1	0	0	0	0
	Avg	-1	-1	0	0	0	0
P-2		2(A)	2	4	5	7	10
		2(A)	3	4	8	10	12
		2(A)	3	5	9	12	15
	Avg	2	3	4	7	10	12
P-3		1	3	4	6	8	10
		1	2	5	6	8	10
		2	5	9	11	12	13
	Avg	1	3	6	8	9	11
P-4		7	9	9	11	12	13
		6	9	9	13	13	13
		7	11	14	14	16	--(B)
	Avg	7	10	11	13	14	14
P-5		0	-1	-1	-1	-1	-1
		0	-1	-1	-1	-1	-1
		0	0	0	-1	-1	-1
	Avg	0	-1	-1	-1	-1	-1
P-6		0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0	0	0	0
	Avg	0	0	0	0	0	0
P-8		6	15(C)	17	17	19	21
		3	4(C)	8	11	15	18
		4	11	13	17	19	21
	Avg	4	10	13	15	18	20
P-9		2	3	3	4	4	5
		2	2	3	4	4	4
		1	1	1	2	2	1
	Avg	2	2	2	3	3	3

Note: Negative weight loss indicates weight gain, possibly due to absorption of moisture in pores after surface film was eroded.

(A) = 18-hr period.

(B) = Mortar burned out; test discontinued after 60 hr.

(C) = 27-hr period.

Table 5

Freeze-Thaw Test Results

ASTM C 666 (ASTM 1987c)

Product Code		Percent of Original Weight at Number of Cycles Shown									
		27	53	87	120	156	186	214	246	279	312
		Cement-Based Materials									
P-2		100	100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100	100
	Avg	100	100	100	100	100	100	100	100	100	100
P-3		100	100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100	100
	Avg	100	100	100	100	100	100	100	100	100	100
P-4		100	100	100	100	100	100	100	100	100	100
		100	101	101	101	101	*				
		100	100	100	100	100	101	100	101	101	100
	Avg	100	100	100	100	100	100	100	100	100	100
P-8		100	99	93	73	52				Specimens broke	
		100	99	95	88	82	74	67	54	}in half; stopped	
		100	100	92	79	63	41			test.	
Avg		100	99.3	93.3	80	65.7	56	53	49		

		Percent of Original Weight at Number of Cycles Shown								
		36	71	110	146	185	220	248	277	303
		Epoxy Materials								
P-1		100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100
	Avg	100	100	100	100	100	100	100	100	100
P-5		100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100
	Avg	100	100	100	100	100	100	100	100	100
P-6		100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100
		100	100	100	100	100	100	100	100	100
	Avg	100	100	100	100	100	100	100	100	100
P-9		101	101	101	101	101	101	101	101	101
		101	102	102	102	102	102	102	102	102**
		101	103	102	102	102	103	102	102	102
	Avg	101	102	101.7	101.7	101.7	102	101.7	101.7	101.7

* Split where layered.
** Cracked on edge.

Table 6

Impact Resistance Test

Product Code		Drop Height, in.	Kinetic Energy in.-lb	Type of Damage
P-1		6	510	Broke in two pieces
		12	1,020	Broke in two pieces
		18	1,530	Broke in three pieces
	Avg	12	1,020	
P-2		3	255	Broke in three pieces
		2	170	Broke in two pieces
		3	255	Broke in four pieces
	Avg	2-2/3	227	
P-3		3	255	Broke in three pieces
		3	255	Broke in two pieces
		3	255	Broke in three pieces
	Avg	3	255	
P-4		3	255	Broke in two pieces
		3	255	Broke in three pieces
		3	255	Broke in two pieces
	Avg	3	255	
P-5		14	1,190	Broke in two pieces
		9	765	Broke in three pieces
		17	1,445	Broke in three pieces
	Avg	13-1/3	1,133	
P-6		13	1,105	Broke in two pieces
		16	1,360	Broke in two pieces
		16	1,360	Broke in four pieces
	Avg	15	1,275	
P-8		2	170	Broke in two pieces
		3	255	Broke in three pieces
		2	170	Broke in two pieces
	Avg	2-1/3	198	
P-9		5	425	Broke in three pieces
		5	425	Broke in three pieces
		5	425	Broke in two pieces
	Avg	5	425	

Table 7

Thermal Expansion Tests of 3- by 3- by 11-1/4-in. Prisms With 10-in. Nominal Gage Length

Product Code		Thermal Expansion Millionths/°F	Product Code		Thermal Expansion Millionths/°F
P-1		19.3	P-5		13.4
		20.5			14.0
		21.2			13.5
	Avg	20.3		Avg	13.6
P-2		3.5	P-6		28.0
		4.4			26.0
		4.2			27.0
	Avg	4.0		Avg	27.2
P-3		6.0	P-8		2.5
		7.2			2.0
		6.1			2.6
	Avg	6.4		Avg	2.4
P-4		3.5	P-9		16.2
		4.3			15.2
		4.3			16.3
	Avg	4.0		Avg	15.9

Table 8

Concrete Patching Compounds 1987 Cost Evaluation

Product Code	Approximate Cost per cu ft
P-1	$136.00
P-2	39.00
P-3	55.00
P-4	81.00
P-5	169.00
P-6	143.00
P-8	37.00
P-9	53.00

Table 9

Overall and Generic Product Performance Ratings

Evaluation Parameter	Overall Ranking								Epoxies				Cements			
	1	2	3	4	5	6	7	8	1	2	3	4	1	2	3	4
Bond, wet (slant-shear)	1	2	3	4	6	5, 9	-	8	1	6	9	5	2	3	4	8
Bond (tension)	5	2	3	4	8	6	9	1	5	6	9	1	2	3	4	8
Bond (flexural)	5	1	6	3	2	9	8	4	5	1	6	9	3	2	8	4
Abrasion	1, 5, 6	-	-	9	3	2	4	8	1, 5, 6	-	-	9	3	2	4	8
Resistance to freezing and thawing	1-6, 9	-	-	-	-	-	-	8	1, 5, 6, 9	-	-	-	2, 3, 4	-	-	8
Impact	6	5	1	9	3, 4	-	2	8	6	5	1	9	3, 4	-	2	8
Thermal compatability	3	2, 4	-	8	5	9	1	6	5	9	1	6	3	2, 4	-	8
Cost	8	2	9	3	4	1	6	5	9	1	6	5	8	2	3	4

Product	Overall Performance Rating
5	47
3	46
1	43
2	43
6	40
4	36
9	35
8	23

Epoxy Products	Performance Rating	Cement-Based Products	Performance Rating
5	25	3	28
6	23	2	26
1	23	4	18
9	18	8	12